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Dynamic spatially explicit mass-balance modeling for targeted watershed phosphorus management
II. Model application

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ABSTRACT

Cost-effective nonpoint source phosphorus (P) control should target the land areas at greatest risk for P loss. We combined mass-balance modeling and geographic analysis to identify and map high-risk areas for P export by integrating long-term P input/output accounting with spatially variable physiographic, land use, and agronomic factors. The dynamic interactive simulation of phosphorus loss areas (DISPLA) model evaluates changes over time and space in soil P concentration and P export in response to management interventions targeted specifically to critical P source areas. Five scenarios were simulated in a test watershed dominated by dairy agriculture in Vermont's Champlain Valley: (1) baseline; (2) nutrient management applied to corn and hay land and to urban lawns; (3) erosion control applied to silage corn land; (4) conversion of critically eroding cropland to permanent grass; and (5) all management changes combined. If present-day conditions continue, soil test P and P export will inevitably increase as P inputs continue to exceed outputs. Soil test P levels on corn land are projected to increase more than fourfold over 80 years if present management continues; estimated P export is expected to more than double over the same period. Increases in soil test P over time in the watershed are not uniform, but varied spatially in response to variability in initial conditions and input/output P balance. Targeted nutrient management was effective in reducing soil test P concentrations (50–90%) and appeared to hold the line on P export for the test watershed over the 80-year simulation. Simulated P export in the test watershed at the end of the nutrient management simulation was reduced by 64% compared to baseline. Implementation of erosion control on row cropland had little effect on soil test P and achieved only a transitory reduction in P export. Exclusive reliance on cropland erosion control to manage nonpoint source P is unlikely to succeed over the long term. Conversion of critical row cropland to permanent grass reduced P export by 54%, but did not affect soil P levels. Because row cropland converted to grassland retains its soil test P concentration, management of converted grassland to reduce runoff and P export is very important; row cropland with elevated soil test P converted to riparian buffer may still serve as a source of dissolved P to runoff. Application of all management measures combined yielded a 74% reduction in P export. Implications to watershed P management are discussed.

1. Introduction

Watershed models are widely used in environmental management to estimate or predict water quantity and quality conditions. Application of models helps managers understand pollutant sources and pathways and prioritize sources for treatment. Perhaps most importantly, models are used to forecast future outcomes, to predict the effects of management decisions on water quantity and quality. Such models are frequently used to evaluate treatment alternatives and to inform decisions about how best to allocate resources for the protection and improvement of water quality.

All models use mathematical equations to calculate results of interest like streamflow or pollutant load. Models may be

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theoretical, using understanding of fundamental principles described by equations, or empirical, using regression equations, for example, derived from observed data. Models may be classified as deterministic or stochastic. Deterministic models do not allow model parameters to vary randomly; such models will always produce the same result from the same initial conditions. Stochastic models allow one or more model parameters to vary randomly around some probability distribution and yield a distribution of results. Models such as AGNPS (USDA-ARS, 2006a) may simulate an individual storm event; others such as SWAT (USDA-ARS, 2006b) may produce a continuous simulation over an entire annual cycle.

Some watershed models are considered to be "lumped models", they do not take into account spatial variability of inputs, outputs, or model parameters, but rather use mean or representative values for watershed characteristics. In contrast, distributed models include spatial variation in inputs, outputs, and parameters, often by dividing the watershed area into a number of elements and conducting simulations separately for each element. Models such as HSPF (USGS, 2006) occupy a middle ground, representing spatial variability by subdividing a watershed into segments and using representative parameters for each segment.

Regardless of whether a watershed model is theoretical or empirical, deterministic or stochastic, lumped or distributed, few, available models do a complete job of simulating spatial variability on the output side. While some distributed models such as AGNPS (USDA-ARS, 2006a) rely heavily on spatially explicit inputs like slope, soil type, or land use in a watershed, model outputs are usually restricted to streamflow, concentration, or load at one specific point, usually the watershed outlet. Although such information is highly valuable in many situations (e.g., a TMDL exercise), it may not address all management needs, such as the need to target treatment interventions to the most critical areas within a watershed. Heathwaite et al. (2003) developed a spatially explicit Phosphorus Indicators Tool to identify high-risk areas for P loss within a watershed based on an assessment of land use, management, and environmental factors at a specific point in time.

However, most existing watershed phosphorus (P) models fail to account for a common temporal trend of ongoing watershed P enrichment, driven by a long-term imbalance of P inputs and outputs. In watersheds dominated by intensive animal agriculture, over-application of nutrients relative to crop need often results in accumulation of P in agricultural soils at the farm (Klausner, 1995; Koelsch and Lesoing, 1998) and the watershed scale (McMahon and Woodside, 1997; Cassell et al., 1998). Excessive soil P levels drive high-P losses in runoff, especially in areas of animal-based agriculture (Breeuwsma et al., 1995; Pote et al., 1996; Lander et al., 1998; Sims et al., 2000). Soil P content is determined by management activities (e.g., animal waste application, cropping) and by soil characteristics (e.g., drainage class, P sorption characteristics). All of these conditions vary spatially. Areas of excessive soil P also vary in time in response to the process of P accumulation or depletion due to imbalance between inputs and outputs.

Watershed P management, including application of models, must address issues of long-term accumulation of surplus P that threaten water quality. As Kleinman (2000) pointed out, management of P source risk requires understanding not only of nutrient sources, soil properties, cropping system management, and new management practices but also the issue of balance between nutrient inputs and outputs. Jokela et al. (2004a) reviewed research on various BMPs to reduce P loading in the Champlain basin of VT-NY, and similarly concluded that to be effective such efforts must address the issue of P imbalance in the watershed.

Watershed P management must also address the issue of targeting. The predominant approach to the implementation of improved agricultural management in a watershed relies on entirely voluntary, incentive-driven participation, with all watershed producers equally eligible to participate. This approach conflicts with the reality of spatially variable P source areas and spatially variable runoff transport mechanisms that deliver nonpoint source P from land to water. To be more cost-effective, implementation of management measures to reduce nonpoint source P export from the land should be targeted to the land areas at greatest risk for P loss.

We developed an approach to analyze, identify, and map high-risk areas for P export by coupling a long-term P mass-balance simulation model running in grid cells across a watershed with spatially variable physiographic, land use, and agronomic data. The temporal and spatial relationships that define the risk of P export are captured simultaneously using a raster-based distributed dynamic modeling approach and are related to management interventions. We predicted response to management interventions and displayed results spatially through a geographic information system (GIS). This approach allows the spatial distribution of P runoff risk to be tracked through time in response to long-term P input/output balance, resulting from either continuation of current practices or from management changes targeted to areas of high-P loss risk. The resulting model can assist scientists and watershed managers in targeting management interventions to critical source areas that present high risk of P loss to surface water and to visualize the response to management over time. Results will contribute to improved targeting of scarce resources to address watershed P management and will enhance management effectiveness by focusing resources on the most critical P source areas within a watershed.

The previous paper (Meals et al., 2008) described the development of the dynamic interactive simulation of phosphorus loss areas (DISPLA) model. This paper describes the application of DISPLA to selected management scenarios in a test watershed and discusses the implications of results for watershed P management.

2. Methods

2.1. Model background

The fundamental building-block of DISPLA is a unit mass-balance model (the *PPBalModel*) that computes a comprehensive accounting of rates at which P enters and leaves a homogeneous land unit (pixel) on an annual time step. DISPLA includes the Vermont adaptation of the Phosphorus Index (Lemunyon and Gilbert, 1993; Jokela, 2005), and incorporates the concept of variable runoff-contributing areas (RCAs) as an index of P transport potential by surface runoff.

The DISPLA model is integrated in the spatial modeling environment (SME), a software tool that allows the unit mass-balance model to be simultaneously executed across a complex multi-pixel (raster) landscape at an annual time step over periods of decades or more (Maxwell and Costanza, 1997; Costanza and Voinov, 2001; Maxwell, 2003). We used the capabilities of *Arc GIS* (ESRI, Inc.) to prepare, organize, tabulate, and analyze spatial data necessary for input into the modeling system and to display results of model simulations.

2.2. Test watershed/data development

We combined actual data from the Little Otter Creek Watershed in Addison County, Vermont, USA (Fig. 1) with parameters estimated from published sources to construct a test watershed

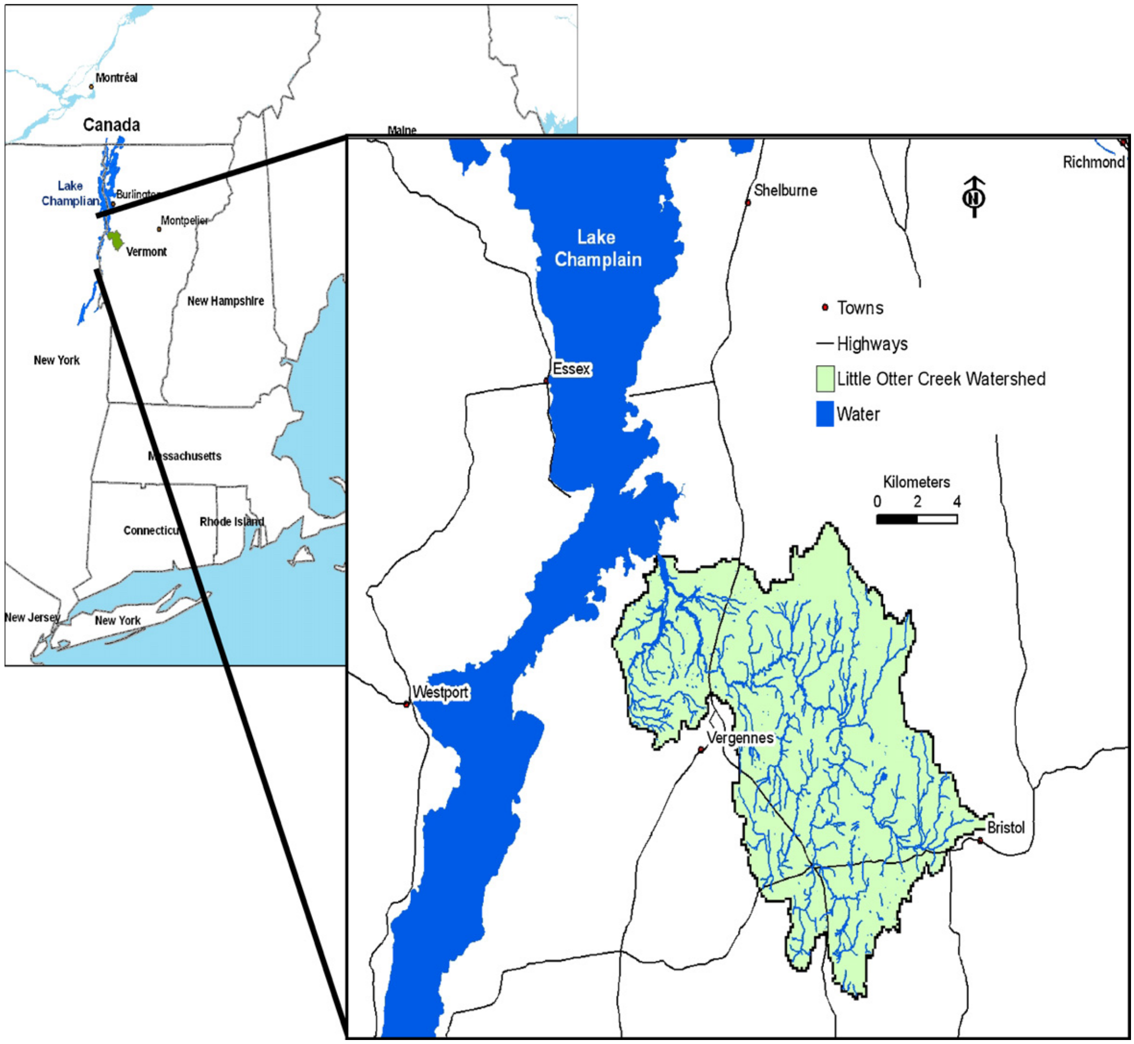

Fig. 1. Location map for test watershed.

representative of agricultural watersheds in Vermont's Champlain Valley. We selected the Little Otter Creek (LOC) watershed because it is composed of a mix of agricultural, forest and urban land, because it is a significant contributor of P to Lake Champlain, which is impaired by high levels of P, and because several key input datasets had already been developed (Parsons et al., 2002).

The LOC watershed occupies 18,460 ha, with an elevation range of 22–416 m above mean sea level. The watershed extends from the Champlain Valley plains in the west to the forested foothills of the Green Mountains in the east. The area has a cool, continental climate, with cold winters, warm summers, and a short growing season. Annual mean daily temperature is 7.5 °C; the frost-free period averages ~200 days. Annual precipitation averages 89 cm.

Soils in the LOC watershed include till soils in the forested uplands and lacustrine clays in the valley plains. The predominant soil series are Vergennes clay (Glossaquic Hapludalfs), Covington (Mollic Endoaqualfs), and Farmington (Lithic Eutrudepts) (USDA-SCS, 1971). Overall, watershed soils are evenly divided between clay and non-clay soil texture. About 80% of watershed area is underlain by hydrologic group C or D soils, indicating moderate to high runoff potential.

The watershed is predominantly agricultural (>50%), with significant forested area (39%), and a small amount of urban land (5%). Agriculture in the LOC watershed is mainly dairy, with an estimated 54 farms housing some 8300 animal units (1 animal unit = 453 kg animal weight). The primary crops produced in the watershed are silage corn and mixed grass and/or alfalfa hay.

Primary geospatial datasets – digital elevation model (DEM), land use, soil series, and initial soil test P – were obtained from existing sources or were estimated using the best available information, including knowledge from researchers, professionals, farmers, and other regional and local stakeholders. We used ESRI's *Arc GIS* and *Spatial Analyst* (http://www.esri.com) to prepare vector and raster data, respectively. Raster data are spatial data made-up of a grid of cells (pixels), unlike "vector" data that comprise points, lines and polygons. *Arc GIS* was also used to overlay and manipulate fundamental data layers such as the DEM, soil series, hydrography, and land use class prior to input to the model. All input data sets were converted into raster landscapes for input into SME. We used a 60 m × 60 m pixel size as a reasonable compromise between the desired level of detail and the need to keep the landscape to a manageable size for existing computer resources.

We used a DEM based on a USGS 7.5 min quadrangle comprised of a 30 m × 30 m grid) estimated to have a vertical root mean square error of 7 m (VCGI, http://www.vcgi.org/).

Land use data were originally extracted from 1993 Landsat Thematic Mapper™ imagery, subsequently edited and corrected using 1:5000 digital orthophoto quadrangles and ground checking. The resulting 23 land use/land cover categories were aggregated to five general categories for this study: corn, hay/pasture, forest, urban, and other. The "other" category represented a mix of land uses including farmsteads, open or idle land, and roads that did not participate in the simulations.

The original land use coverage did not distinguish between hay land and pasture land. However, management of these two types of grassland differs significantly with respect to P inputs and outputs. Hay land consists of various mixtures of legumes (primarily alfalfa or clover) and grasses and typically receives several applications of animal waste annually and often some inorganic P fertilizer; vegetation is harvested two to three times annually. Pasture typically receives only manure deposited from grazing livestock, no inorganic P fertilizer, and vegetation is removed only by grazing animals. Grassland was partitioned between hay and pasture based on two assumptions: (1) consistent with other agricultural watersheds in the region, we assumed 30% of grassland to be hay and 70% to be pasture and (2) hay tends to grown on more level areas where machinery can be easily used, while steeper, rockier land is usually relegated to pasture. We applied these assumptions separately to 18 sub-basins of the LOC watershed so that all pasture land would not be allocated to the steeper eastern region. Thus, for each of the 18 sub-basins, the 70% steepest grassland pixels were classified as pasture, while the remaining grass pixels were classified as hay land.

Soils data were obtained that had been digitized from the 1971 Addison County National Resources Conservation Service (NRCS) soil survey at a level that meets the National Cooperative Soil Survey (NCSS) mapping standards. The data set included hydrologic soil group, soil bulk density, soil texture, and soil erodibility (k) factor for use in the RUSLE (USDA-ARS, 2006c).

The *PPBalModel* requires initial soil test P for each pixel as an input parameter. Unfortunately, such data do not exist for the LOC watershed. General data from agricultural soil tests in Addison County for the past decade were provided by the University of Vermont Agricultural Testing Laboratory; these tests report soil test P analyzed by the Modified Morgan extraction (Jokela et al., 2004a,b) as mg P kg^{-1} dry soil. Lab results were attributed to land use (corn, hay, or pasture), but no data on soil type were associated with the results. Based on general relationships between land use and soil test P and professional judgment, default initial soil test P levels were assigned by pixel land use: corn –9.0 mg P kg^{-1}; hay –6.0 mg P kg^{-1}; pasture –5.5 mg P kg^{-1}; urban –15 mg P kg^{-1}; and forest –3.0 mg P kg^{-1}. Based on agronomic judgment, these default values were adjusted based on soil texture, increasing initial soil test P concentration by 15% on clay soils. In Vermont, a soil test P of 4–7 mg P kg^{-1} is considered optimum for crop production; values from 7 to 20 are considered high, and values exceeding 20 are classified as excessive (Jokela et al., 2004a,b).

Soil reactive aluminum affects how much P added in manure or fertilizer is adsorbed in Vermont soils (Jokela et al., 1998; Magdoff et al., 1997, 1999) and is an element of the Vermont P Index (Jokela, 2005a). Soil aluminum concentrations were therefore also required for each pixel in the LOC. Because such data do not exist for the LOC, we assigned representative values (ranging from 40 to 51 mg kg^{-1}) to each pixel on the basis of soil type, using general data from analyses of Vermont soils (Jokela, 2005b).

We calculated additional model input parameters from the primary data layers described above. We determined curve numbers (USDA, 1985) from land use and hydrologic soil group, assuming good hydrologic condition and antecedent moisture condition II. We estimated representative values for parameters for the RUSLE in consultation with NRCS State Office staff. We calculated the wetness index (Tarboton, 2002) from the DEM. Finally, we assigned runoff-contributing area probability based on curve number, design rainstorms, and wetness index as described in Meals et al. (2008).

Our confidence in the values selected for all of these parameters was enhanced by the involvement of a Project Advisory Committee consisting of representatives from state agricultural and conservation agencies, municipal and state officials, an Extension agronomist, and watershed community members.

2.3. Scenarios

We conducted five simulations to project the long-term effects of current management and to evaluate the effects of new management measures (i.e., Best Management Practices, BMPs) on P dynamics in the test watershed:

1. *Baseline*: present-day conditions of P inputs and management remain constant into the future;
2. *Nutrient management*: improved nutrient management applied to corn and hay land; P fertilizer additions to urban land limited;
3. *Erosion control*: best practical erosion control measures applied to corn land, including changes in tillage, rotations, and row arrangement;
4. *Land use change*: conversion of some corn land to permanent hay land; and
5. *All practices*: all of the above management changes combined.

These scenarios are described in detail below.

Table 1
Thresholds and P inputs for Nutrient Management Scenarios

Level	STP[a] threshold (mg P kg^{-1})	Manure P (kg P ha^{-1})	Fertilizer P (kg P ha^{-1})	Total P input (kg P ha^{-1})	Crop removal[b] (kg P ha^{-1})	P balance[c] (kg P ha^{-1} year^{-1})
Corn						
Default	–	52.9	28.8	81.7	48.2	+33.5
1	>10	19.4	19.4	38.8		–9.4
2	>20	0	9.5	9.5		–38.7
3 (remedial)	<2	24.1	28.8	52.9		–4.7
Hay						
Default	–	23.6	14.6	38.2	32.5	+5.7
1	>10	10	14.6	24.6		–7.9
2	>20	0	14.6	14.6		–17.9
3 (remedial)	<2	24.6	14.6	39.2		+6.7
Urban						
Default	–		8.6	8.6	–	
1	Time = 30		3.9	3.9		

[a] Modified Morgan P extraction.
[b] Crop P removal at average yield, Jokela et al. (2004a,b).
[c] Difference between total P input and crop removal.

2.3.1. Nutrient management

Phosphorus inputs and thresholds for nutrient management practices are shown in Table 1. For both corn and hay pixels, default P applications in both manure and inorganic fertilizer represent our best judgment of current representative P application rates in the absence of a nutrient management plan. Note that especially for corn, total P application rate significantly exceeds crop removal rate. Agricultural nutrient management was applied in two levels. Level 1 represents a moderate nutrient management program for high-P soils, triggered when soil test P in a pixel substantially exceeds the optimum level for crop production. Level 2 simulates a rigorous program to drastically cut inputs to soils with excessive levels of P, triggered when a pixel soil test P exceeds 20 mg kg^{-1}. Because both levels of nutrient management supply P at less than crop need, soil P levels will eventually fall below the minimum required for adequate crop production. Therefore, a third "remedial" level of nutrient management can be invoked when soil test P falls into the "Low" category, below 2 mg kg^{-1}. Thus, the nutrient management measure strives to manage soil test P to maintain soil P levels between 2 and 10 mg kg^{-1}.

Urban nutrient management is applied on a time trigger (year 30) to mimic the adoption of a municipal ordinance restricting the use of lawn fertilizers. After nutrient management is triggered, atmospheric deposition is the only remaining P input to urban pixels.

2.3.2. Erosion control

Baseline erosion condition for corn land was defined by the Vermont NRCS State Office as Fall moldboard tillage, no winter cover crop, 5 years of silage corn followed by 5 years of hay. Simulated erosion control to corn land defined by NRCS included application of Fall chisel plow, spring disk; 4 years of silage corn followed by 5 years of hay; row arrangement planted across the predominant slope; and application of strip cropping. These practices were modeled by adjusting the RUSLE crop factor (C) from 0.0157 to 0.0146, and the practice factor (P) from 0.9 to 0.65.

During the simulations, application of erosion control to pixels in corn was based on time and RCA criteria. In simulation year 10, erosion control was applied to all corn pixels with an RCA probability of 1.0 (those expected to generate runoff annually). In simulation year 20, erosion control was applied to corn pixels with an RCA probability of 0.5 (those expected to generate runoff once in 2 years). This approach approximates an erosion control program based on a priority ranking of erosion potential. Once applied, erosion control remained active in a pixel for the duration of the simulation.

2.3.3. Land use change

The land use change measure simulates conversion of critical row cropland to permanent vegetative cover when the P Index exceeds a value of 75. This change was a one-time event and pixels could not revert to corn when the P Index dropped below the threshold. A converted pixel began to receive inputs (e.g., manure and fertilizer P) and produce outputs (e.g., soil loss, runoff P) based on its new land use immediately, but inherited soil test P from its former land use. It should also be noted that conversion from corn to hay is triggered by P Index value alone and is not constrained by realities of agricultural production that would tend to require some minimum amount of corn production based on herd sizes and feeding requirements.

2.3.4. All management

All of the management changes in the previous scenarios are available to be implemented, based on the same triggers and thresholds given above. The timing of the management changes was adjusted to allow better visualization of the sequential effects of the different measures.

It must be noted that all the management measures were implemented based on triggers and thresholds according to characteristics of individual pixels. Thus, for example, nutrient management was not applied to all corn land in the watershed as might be the objective in a contemporary conservation program but in a highly targeted manner only when specific criteria were met. We recognize that such a program can be unrealistic. Nutrient management or erosion control on a few 3600 m^2 pixels in a 30 ha corn field, for example, would likely be impractical in Vermont. Strict nutrient management might require export of manure out of the watershed. Consequences of conversion of some corn land to hay and restriction of P application rates would require changes in farm management. However, the purpose of this exercise was to illustrate what might be achieved by a high level of targeting, in contrast to traditional voluntary watershed-wide approaches, so these constraints were not addressed.

3. Results

Results of baseline simulations (i.e., current conditions extrapolated into the future) were presented in the previous paper (Meals et al., 2008). Results of the new management scenarios are compared with baseline results below. Simulations were conducted for a period of 80 years from present day. Note that for all scenarios management changes began after at least 10 years of baseline simulation.

3.1. Nutrient management

Mean annual soil test P (mg kg^{-1}) for all pixels within a land use class across all soil types, initial soil test P, RCA_P, and other pixel characteristics is plotted over the 80-year DISPLA nutrient management simulation in Fig. 2. The reductions in P inputs imposed by nutrient management in year 10 brought about an immediate and sharp decline in soil test P on corn and hay pixels. Similarly, soil test P in urban pixels dropped dramatically as P inputs are reduced in year 30. In both cases, nutrient management reduced P inputs below outputs, resulting in a progressive decline in soil test P. In corn and hay pixels, the decline continued until soil test P reached the critical minimum of 2 mg kg^{-1}. At that point, remedial nutrient management began, leading to a progressive increase in soil test P, until nutrient management is again invoked by elevated soil test P. Soil test P on hay pixels oscillated between

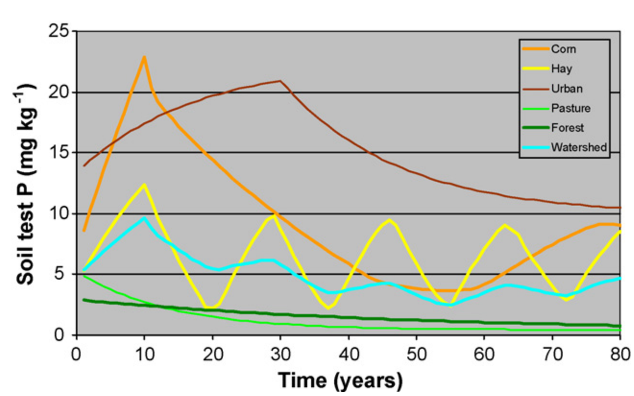

Fig. 2. Plot of pixel-average soil test P (mg kg^{-1}) in pixels of different land uses in the test watershed generated by DISPLA in the nutrient management scenario. Nutrient management practices for corn and hay land become available in year 10; urban nutrient management begins in year 30. No changes are applied to pasture or forest land. Line labeled "Watershed" represents average soil test P across all modeled pixels in the test watershed.

about 2.5 and 10 mg kg^{-1} with a period of about 10 years. The cycle on corn pixels was considerably longer in frequency; the simulation required about 45 years from the onset of nutrient management to first reach the minimum soil test P level. This represents the time required to "mine" the excess P from corn land soils by crop removal and P runoff. Longer DISPLA simulations (not shown) suggest that after this initial depletion of excess P, corn pixels oscillate between about 4 and 8 mg kg^{-1} with a period of about 30 years. The difference in soil test P oscillation periods between corn and hay land is due to the greater imbalance between P inputs and outputs on corn land that requires a longer period to deplete soil P. The decline of soil test P in urban pixels did not show such a cycle because no remedial P inputs are permitted. Soil test P in pasture and forest pixels continued to decline as in the baseline scenario.

Aggregate average soil test P across all land uses (labeled as "watershed" in Fig. 2) declined after nutrient management was invoked and reflects the cyclic behavior exhibited by the corn and hay pixels. At the end of the simulation, average soil test P across the LOC watershed was about 5 mg kg^{-1}, a level comparable to initial conditions. This is considerably lower than the 20 mg kg^{-1} simulated for the same endpoint under baseline conditions (Meals et al., 2008).

Fig. 3 plots annual P export from an average pixel of each modeled land use over the 80-year simulation. The reductions in P inputs imposed by nutrient management brought about an immediate and sharp decline in P export from corn and hay pixels, as well as a decline in P export from urban pixels when urban nutrient management occurs. The sharp discontinuities in the line plotted for corn pixels is a computational artifact, where the model results from one time step overshot a threshold, requiring a correction in the next time step.

The same cyclic behavior was demonstrated in P export as for soil test P. Note that even under the stringent limits of the nutrient management scenario, it takes decades or more to fully realize the reductions in P export. Implementation of nutrient management appeared to hold the line on P export in the LOC watershed over the 80-year simulation; simulated average P export was actually reduced slightly from ~0.44 kg ha^{-1} year^{-1} in year 1 to ~0.39 kg ha^{-1} year^{-1} in year 80. In the baseline scenario, simulated average pixel P export for the watershed was ~1.09 kg ha^{-1} year^{-1} in year 80 (Meals et al., 2008).

Fig. 4 shows mean annual P export from the entire modeled LOC watershed, with annual export averaged within decades.

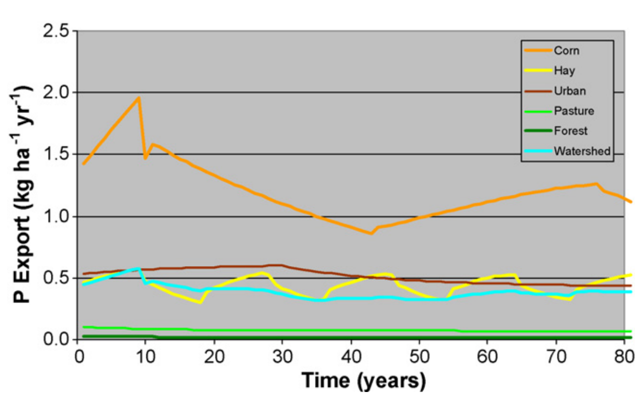

Fig. 3. Plot of pixel-average P export (kg ha^{-1} year^{-1}) from pixels of different land uses in the test watershed generated by DISPLA in the nutrient management scenario. Nutrient management practices for corn and hay land become available in year 10; urban nutrient management begins in year 30. No changes are applied to pasture or forest land. Line labeled "Watershed" represents average P export across all modeled pixels in the test watershed.

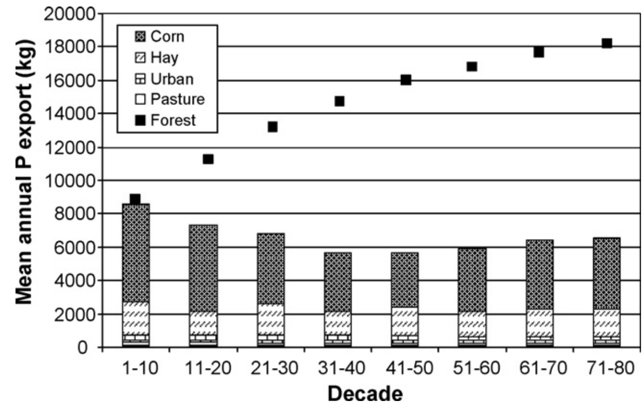

Fig. 4. Plot of total annual P export from modeled pixels in the test watershed, averaged within decades of the simulation, as projected by DISPLA in the nutrient management scenario. Nutrient management practices for corn and hay land become available in year 10; urban nutrient management begins in year 30. No changes were applied to pasture or forest land. Solid squares represent total annual P export under baseline conditions.

Unlike the "average pixel" data plotted in Fig. 3, the data plotted in Fig. 4 capture the variability of soil test P, RCA$_p$, and P export across the test watershed. Under the nutrient management scenario, corn and hay land continued to make the largest contributions to the aggregate P load, while urban land contributed a smaller proportion (because urban land comprises a very small proportion of land in the test watershed). P export from pasture and forest land, unaffected by nutrient management, was negligible. Clearly, the implementation of nutrient management on high soil test P pixels was effective in reducing P export. At the end of the baseline simulation, simulated P export from all pixels in the LOC watershed was 18.5 t year^{-1} (Meals et al., 2008); with implementation of nutrient management on high soil test P corn and hay land and on urban land, simulated export at the end of the nutrient management simulation was 6.5 t year^{-1}. This represents a 64% reduction in P export resulting from targeted nutrient management.

DISPLA also portrays spatial patterns of responses to targeted P management. Fig. 5 presents maps of changes in soil test P compared to baseline for the test watershed resulting from DISPLA simulation of the nutrient management scenario. In these maps, higher values represent greater reductions in soil test P compared to baseline. Thus, in the left panel, the yellow areas represent pixels where soil test P was reduced by up to 30 mg kg^{-1} in year 20 after 10 years of nutrient management, compared to what soil P levels would have been without nutrient management. By year 50 (right panel), simulated soil test P levels in some areas of the test watershed were up to 80 mg kg^{-1} lower than they would have been without nutrient management.

Fig. 6 maps changes in estimated annual P export from pixels of the test watershed predicted by DISPLA for the nutrient management simulation. As with soil test P, in year 20 (left panel), 10 years of nutrient management resulted in simulated reductions of P export by as much as 3 kg ha^{-1} year^{-1} compared to baseline. By year 50 (right panel), P export from some areas was estimated to be reduced by 9 kg ha^{-1} year^{-1}. Again, areas of reduction in P export were not uniformly distributed across the LOC watershed, but were scattered across the landscape and represent a minority of watershed land. This pattern is a result of two factors. First, nutrient management was applied only to areas of high soil test P, not uniformly across the watershed. Second, because P export is driven by runoff, areas of highest simulated export reduction occurred in areas of high probability of runoff. The light blue polygons in Fig. 6 enclose areas with RCA$_p$ = 1.0, and it is apparent

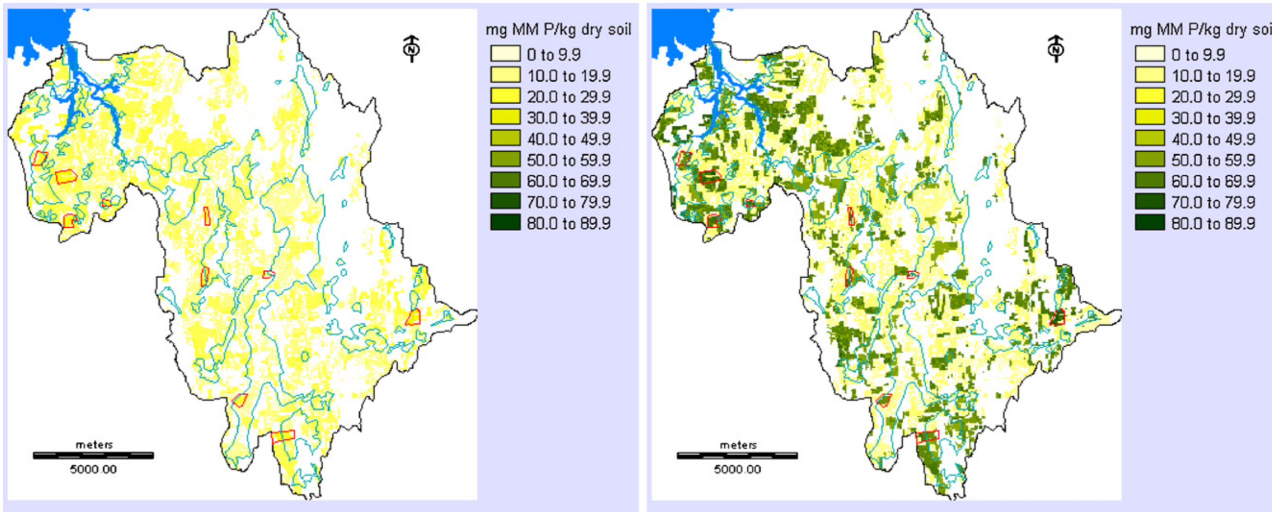

Fig. 5. Maps of differences in soil test P in test watershed pixels between baseline and nutrient management scenarios simulated by DISPLA in year 20 (left panel) and in year 50 (right panel). Higher values represent greater decreases in soil P with nutrient management. Polygons outlined in red indicate zones of elevated initial soil test P. Areas of 1.0 RCA_p are outlined in light blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

that most of the pixels showing the largest change in P export were contained within these regions.

3.2. Erosion control

Only corn pixels were eligible for implementation of erosion control. In simulation year 10, erosion control was applied to all corn pixels with an $RCA_p = 1.0$, then to those in $RCA_p = 0.5$ in year 20. For average corn pixels in $RCA_p = 1.0$, simulated erosion control reduced RUSLE-estimated soil loss by 33%, from 1.7 to 1.1 t ha^{-1}.

Because erosion control practices do not affect P inputs and, while influencing P export in soil loss, do not affect the actual concentration of P in soils (except by selective transport of fine particles that may be enriched in P, a process not modeled in DISPLA), the erosion control scenario had no effect on modeled soil test P concentrations.

Fig. 7 plots annual P export from an average pixel of corn land and from the mean of all pixels in the LOC watershed over 80 years in the erosion control scenario. Implementation of erosion control on corn land had only a small and transient impact on P export. In the erosion control scenario, trends in P export are directly driven not by trends in soil test P but by changes in export of particulate P resulting from reduction in pixel soil loss. Mean P export from corn pixels dropped from ~1.96 to ~1.83 kg ha^{-1} $year^{-1}$ in the first year after erosion control was first implemented, but then P export continued its inexorable increase because P inputs continued to exceed outputs, as shown in the baseline scenario. Effects of the second wave of erosion control were negligible because there were few corn pixels with $RCA_p = 0.5$. The net effect on the average LOC watershed pixel was even smaller. At the end of the erosion control simulation in year 80, average pixel P export was decreased by only 4–5% for corn pixels and overall LOC watershed pixels compared to baseline. Aggregate P export from all modeled pixels was ~17.6 t $year^{-1}$, compared to ~18.5 t $year^{-1}$ for the same period in the baseline simulation, a 5% reduction.

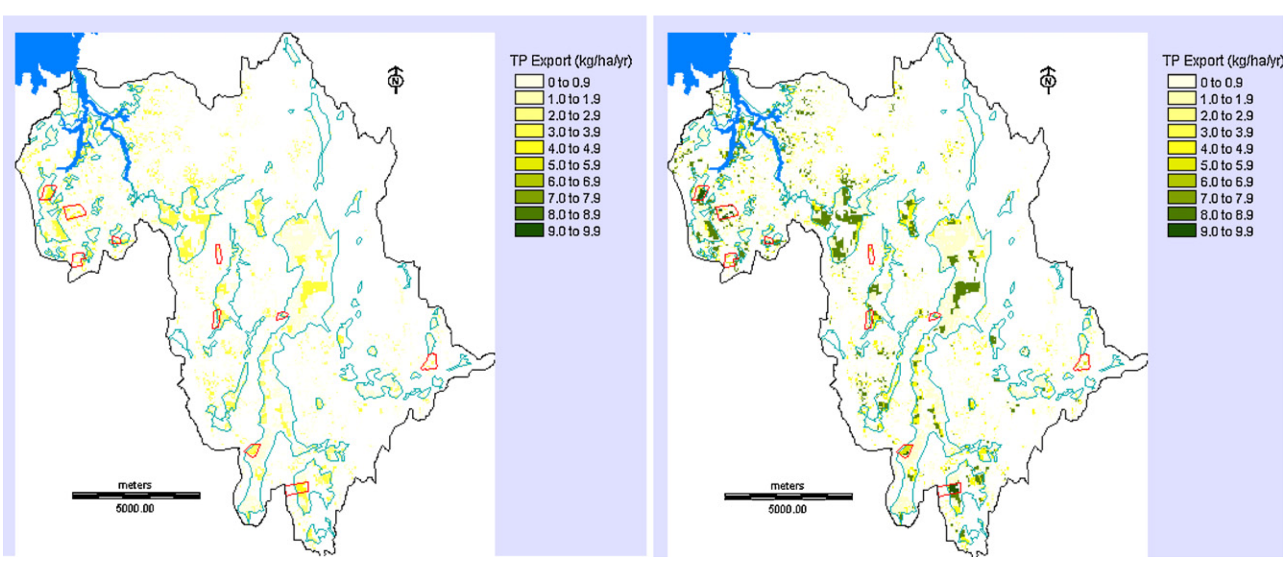

Fig. 6. Maps of differences in P export from test watershed pixels between baseline and nutrient management scenarios simulated by DISPLA in year 20 (left panel) and in year 50 (right panel). Higher values represent lower TP export with nutrient management. Polygons outlined in red indicate zones of elevated initial soil test P. Areas of 1.0 RCA_p are outlined in light blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

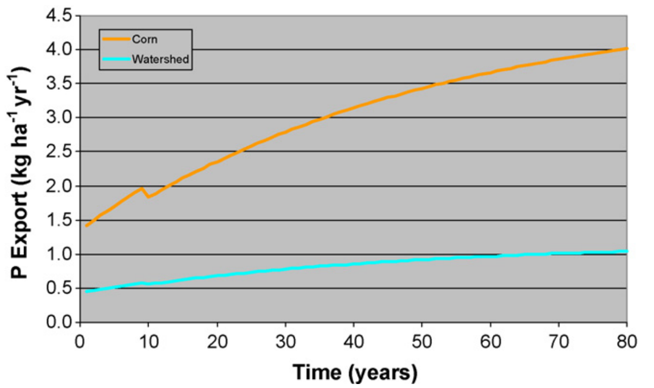

Fig. 7. Plot of pixel-average P export ($kg^{-1}\ ha^{-1}\ year^{-1}$) from pixels in the test watershed generated by DISPLA in the erosion control scenario. Erosion control was applied to corn pixels of $RCA_p = 1.0$ in year 10 and to corn pixels of $RCA_p = 0.5$ in year 20. No changes were applied to pixels in other land uses. Line labeled "Watershed" represents average P export across all modeled pixels in the test watershed.

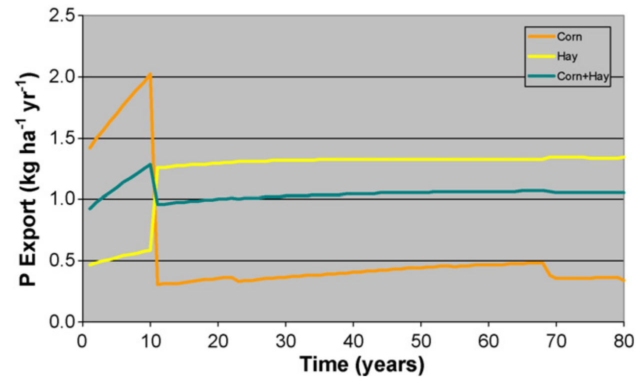

Fig. 9. Plot of pixel-average P export ($kg\ ha^{-1}\ year^{-1}$) from corn and hay pixels in the test watershed generated by DISPLA in the land use change scenario. Opportunity for conversion from corn to hay based on P Index begins in year 10. No changes are applied to urban, pasture, or forest pixels. Line labeled "corn + hay" represents combined average soil test P across all corn and hay pixels in the test watershed at any given time step.

3.3. Land use change

In year 11, 3449 corn pixels (1242 ha) were converted to hay, representing ~35% of corn land in the watershed. Mean annual soil test P ($mg\ kg^{-1}$) in corn and hay pixels is plotted over the 80-year DISPLA land use change simulation in Fig. 8. Mean soil test P in hay pixels, increased ~20% from 12.4 to 15.5 $mg\ kg^{-1}$ between years 10 and 11 as high soil test P was inherited from the previous corn pixels. This elevated soil test P persisted through the end of the simulation—in year 80, mean hay pixel soil test P was 23.9 $mg\ kg^{-1}$, compared to 22.7 $mg\ kg^{-1}$ in the baseline scenario. Interestingly, final mean soil test P in pixels remaining in corn was also higher in the land use change scenario (86.9 $mg\ kg^{-1}$) than in the baseline scenario (80.9 $mg\ kg^{-1}$). Because conversion of corn pixels to hay was triggered by a threshold in the modified P Index (related to P export), most of the converted corn pixels were in the $RCA_p = 1.0$ group. Thus, after year 11, remaining corn pixels were in areas of lower runoff – and hence lower P export – probability. As P inputs in manure and fertilizer continued unchanged, P accumulated in corn pixels at a higher rate because P outputs in erosion and runoff were lower, leading to a greater increase in soil test P over time.

Fig. 9 shows the effects of land use change on P export from corn and hay pixels. The effect of land use change on P export was immediate and dramatic. Because the highest exporting corn pixels were converted first, average P export from corn pixels immediately dropped by ~86%, from 2.0 to 0.3 $kg\ ha^{-1}\ year^{-1}$. Average P export from the remaining corn pixels increased thereafter because P inputs continue to exceed P outputs. Corn pixels continued to be converted to hay through the rest of the simulation at a very low rate. P export from corn pixels remains drastically reduced compared to baseline at the end of the simulation because most of the remaining corn pixels reside in areas of low runoff probability. This decrease did not reflect changes in corn pixel soil test P (see Fig. 8) but was a function of the reduced runoff and export from remaining corn pixels that have low runoff probability.

Export from the average hay pixel, however, increased sharply after conversion because of inherited high soil test P and because the first converted pixels tended to be those with high runoff potential (Fig. 9). This increase from 0.6 to 1.3 $kg\ ha^{-1}\ year^{-1}$ and the fact that after conversion, aggregate P export from hay pixels far exceeds that from corn pixels underscores the importance of soil test P on hay land, even though runoff and erosion rates are typically much lower than those from corn land.

The net effect of land use change on the principal sources of P export in the LOC watershed (plotted as "corn + hay" in Fig. 9) was, however, an immediate 25% reduction in P export from 1.28 to

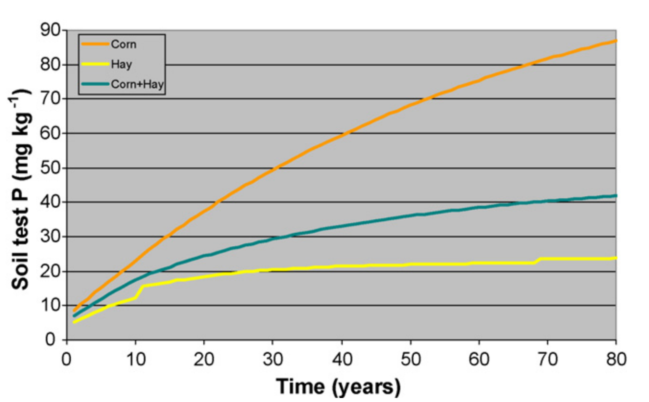

Fig. 8. Plot of pixel-average soil test P ($mg\ kg^{-1}$) in corn and hay pixels in the test watershed generated by DISPLA in the land use change scenario. Opportunity for conversion from corn to hay based on P Index begins in year 10. No changes are applied to urban, pasture, or forest pixels. Line labeled "corn + hay" represents combined average soil test P across all corn and hay pixels in the test watershed at any given time step.

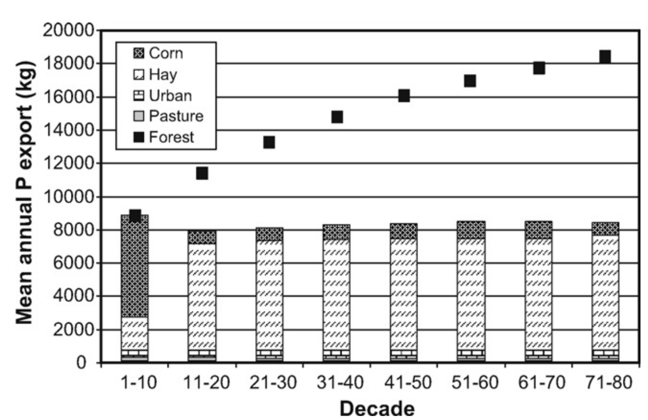

Fig. 10. Plot of total annual P export from modeled pixels in the test watershed, averaged within decades of the simulation, as projected by DISPLA in the land use change scenario. Corn pixels with P Index >75 were converted to hay beginning in year 10. No changes were applied to pixels in other land uses and P export from those land uses is the same as in the baseline scenario. Solid squares represent total annual P export under baseline conditions.

0.96 kg ha^{-1} year^{-1}. Although P export increases gradually after the conversion because P inputs continue to exceed P outputs for both corn and hay, P export pixels is significantly reduced in this scenario compared to baseline.

Fig. 10 shows mean annual P export from the entire modeled LOC watershed over time in the land use change scenario simulation. Total annual P export was reduced immediately by land use change, both from the pre-BMP levels (first decade) and in comparison to the baseline. At the end of the simulation, annual P export in decade 71–80 averages 8.5 t year^{-1}, compared to 18.5 t year^{-1} for the same decade in the baseline scenario, a 54% reduction.

The conversion of critical corn pixels, mainly in RCA$_p$ = 1.0, to hay resulted in dramatically altered distribution of P sources in the watershed. Whereas corn land previously contributed 65–80% of the total annual P export from the watershed, hay land became the principal contributor (~80%). This is significant, especially considering the substantially lower P export rate from hay land compared to corn land and the fact that only about 1300 ha of watershed land was involved in this scenario.

3.4. All management

The final DISPLA simulation allowed all three management measures – nutrient management, erosion control, and land use change – to occur, based on the triggers and thresholds described earlier. The timing of the measures' availability was staggered so that the effects could be more easily visualized: nutrient management—year 10 (agricultural), year 30 (urban); land use change—year 20; erosion control—year 15 (RCA$_p$ 1.0), year 25 (RCA$_p$ 0.5).

The response of soil test P to the All Management simulation was essentially the same as that of the nutrient management scenario (Fig. 2), because nutrient management was the principal management measure that influenced the P input/output balance. The effects of the sequential implementation of management measures on pixel P export are evident in Fig. 11. Average P export from corn and hay pixels dropped immediately in year 11 following the implementation of nutrient management on eligible pixels. A second sharp decrease in mean P export from corn pixels occurred in year 15 as the first wave of erosion control was implemented on corn pixels with RCA$_p$ = 1.0. The largest drop in P export from corn pixels occurred in year 20 with the availability of land use change, along with a concurrent increase in average export from hay pixels. The net result of these forces was a strong decline in P export averaged across all watershed pixels, stabilizing at ~0.3 kg ha^{-1} year^{-1}, compared to the ~1.1 kg ha^{-1} year^{-1} at the end of the baseline simulation.

Fig. 12 shows mean annual P export from modeled pixels in the LOC watershed over time in the All Management scenario simulation. The plot shows both the overall decrease in export brought about by nutrient management and the shift in dominant source of P from corn to hay with land use change. Note that the average aggregate P export over the last decade of the simulation is ~4.8 t year^{-1}, a 74% reduction compared to baseline. The slight increase in P export in the last three decades shown in Fig. 12 is due to an increase in soil test P, caused by oscillations in response to nutrient management.

In the All Management scenario, simulated reductions in P export were the combined result of the achievement of a closer balance between P inputs and outputs (nutrient management) and reductions in P runoff losses (land use change and erosion control).

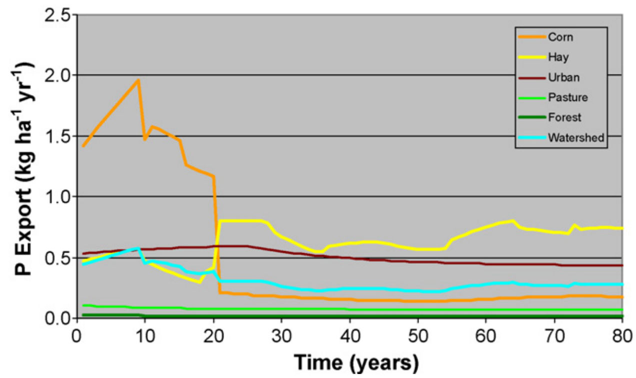

Fig. 11. Plot of pixel-average P export (kg ha^{-1} year^{-1}) from pixels in the test watershed generated by DISPLA in the All Management scenario. Triggers and thresholds for management measures are the same as in individual measure scenarios. In this simulation, nutrient management was available beginning in year 10; erosion control in years 15 and 25 for RCA$_p$ 1.0 and 0.5, respectively; and land use change in year 20. Line labeled "Watershed" represents average P export across all modeled pixels in the test watershed.

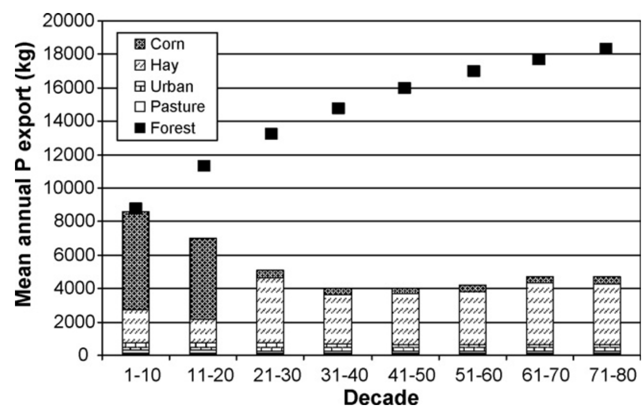

Fig. 12. Plot of total annual P export from modeled pixels in the test watershed, averaged within decades of the DISPLA All Management simulation. Triggers and thresholds for management measures are the same as in individual measure scenarios. In this simulation, nutrient management was available beginning in year 10; erosion control in years 15 and 25 for RCA$_p$ 1.0 and 0.5, respectively; and land use change in year 20. Solid squares represent total annual P export under baseline conditions.

Table 2
Simulated average pixel soil test P and aggregate P export in year 80 of DISPLA simulations

Scenario	Average pixel soil test P (mg kg^{-1})					Aggregate P export (kg year^{-1})						
	Corn	Hay	Urban	Pasture	Forest	Corn	Hay	Urban	Pasture	Forest	Total	% reduction
Baseline	80.9	22.7	22.5	0.4	0.8	15.0	2.8	0.5	0.1	0.1	18.5	–
Nutrient management	9.0	8.6	10.6	0.4	0.8	4.0	1.9	0.4	0.1	0.1	6.6	64
Erosion control	80.9	22.7	22.5	0.4	0.8	14.1	2.8	0.5	0.1	0.1	17.6	5
Land use change	86.9	23.8	22.5	0.4	0.8	0.7	6.9	0.5	0.1	0.1	8.5	54
All management	9.2	8.5	10.5	0.4	0.8	0.4	3.7	0.4	0.1	0.1	4.8	74

Percent reductions refer to reductions relative to results from baseline simulation.

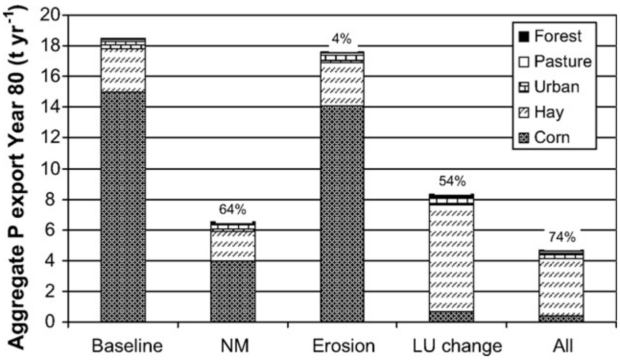

Fig. 13. Plot showing the sum of P export from modeled pixels in the test watershed at the end of 80-year DISPLA simulations. Numbers above bars represent reductions relative to baseline scenario.

By year 50, P export from some areas of the watershed was reduced by 9 kg ha^{-1} year^{-1} or more compared to the baseline scenario. These areas were scattered across the LOC watershed, mainly in the RCA_p 1.0 areas. Overall, a reduction of 74% in aggregate P export was simulated in the All Management scenario.

DISPLA simulations showed that management measures implemented on limited land areas within a watershed can yield substantial reductions in soil P and P export (Table 2 and in Fig. 13). Nutrient management was the most effective single measure for reducing P export and the only practice that affected soil test P by influencing the P input/output balance. Erosion control on row cropland had no effect on soil test P and yielded very little reduction in P export over the long term. Conversion of row cropland to permanent grassland not only reduced overall P export but also shifted the dominant source of P export in the watershed from corn to hay. Implementation of all the management measures simultaneously resulted in the largest simulated reduction in P export from land within the LOC watershed.

4. Discussion

The numerous factors that control the input, output, storage, and flux of P in soils, vegetation, livestock, and water interact simultaneously and change through time. Some of these relationships are synergistic and some are antagonistic; DISPLA and other models give us an opportunity to illuminate the net effects of management decisions and perhaps guide policy decisions for watershed management.

Our simulations were conducted over an unusually long time horizon, certainly exceeding the duration of typical management programs. We believe that there is value in taking a long view of complex environmental problems. Phosphorus enrichment of soils and fresh waters has taken decades to reach crisis proportions in North America and short-term solutions are rare. The significance of gradual, long-term processes may not be appreciated in short simulations. The impact of small annual increases in soil test P, for example, may not seem important until consequences of continuous imbalance over decades can be visualized. Temporary reduction in P export resulting from erosion control might appear as "mission accomplished" in a short view; a long view reveals a different picture (Fig. 7). Finally, a long simulation shows important patterns not obvious in short-term exercises. Long lag times in system response and long-term variability are examples that are discussed below. The days when erosion control and animal waste storage appeared to be immediate solutions to P management are past. The principles illustrated in our simulations can offer some important lessons for future efforts to control P loads.

If present-day management and conditions continue, both soil test P and P export will inevitably increase as P inputs continue to exceed outputs. Increases in soil test P over time are not uniform, but vary spatially in response to variability in initial conditions and in ongoing natural and management processes in the watershed; DISPLA analysis identifies hotspots of projected high soil test P and P export. Recognizing and targeting these hotspots could improve the cost-effectiveness of nonpoint source control programs.

The only way to influence soil test P is to achieve a closer balance between P inputs and outputs; the only management measure we tested that was effective in reducing soil test P was nutrient management. Implementation of nutrient management appeared to hold the line on average pixel P export for the test watershed over the 80-year simulation; simulated P export from all pixels in the test watershed at the end of the nutrient management simulation was reduced by 64% compared to baseline P export.

Implementation of erosion control on row cropland yielded only a transitory reduction in P export and had little or no effect on soil test P. Exclusive reliance on cropland erosion control to manage nonpoint source nutrient loads is unlikely to succeed over the long term.

Conversion of critical P-exporting corn land to permanent hay land reduced aggregate watershed P export, but did not by itself address excessive soil P levels. Because converted grassland retains its high soil test P, management of converted grassland to reduce runoff and P export is very important; row cropland with elevated soil test P converted to riparian buffer, for example, may still serve as a source of dissolved P to runoff. This suggests that P inputs to such land must be managed carefully (e.g., through nutrient management) even if runoff and erosion rates are substantially reduced.

Regardless of land use, runoff-contributing areas are critical to P export within a watershed. Identification and mapping of these areas should be a key component of watershed management efforts. Major runoff-contributing areas, for example, could be targeted for additional management measures or for accelerated soil P testing to monitor watershed status with respect to soil P.

Two notable patterns emerge from the long-term DISPLA simulations. While reductions in soil test P and P export began to occur immediately after implementation of nutrient management, there was substantial lag time – on the order of decades – before a new equilibrium was achieved. Recognition of such lag time must temper expectations in short-term watershed management programs. Secondly, even with the significant reductions from nutrient management, neither soil test P nor P export achieved a constant "equilibrium" level over time. Under realistic agronomic conditions that allow additional P inputs to maintain adequate soil fertility, both soil test P and P export varied between the minimum and maximum limits set by nutrient management practices; these cycles were on the order of decades or more. Such variability would be increased if natural weather variability were included in the simulation. Again, recognition of the likelihood of such variation must temper the notion of fixed loading targets embodied in TMDL programs, for example.

Some important constraints of DISPLA should be mentioned. Simulation results were oversimplified because estimates of some initial conditions were oversimplified and because neither year-to-year variations in weather nor long-term climate change were included. Actual conditions would be considerably less uniform and the response correspondingly more variable, both temporally and spatially. Secondly, baseline simulations did not account for change in the quantity of animal waste or in cropland or urban area in the watershed likely to occur over 80 years. Finally, our model application was not constrained by agronomic realities, such as how to reduce P inputs in manure and fertilizer or how to cope with decreased silage corn production resulting from conversion of corn land to hay. These and other agronomic realities would certainly place some limitations on the implementation of management scenarios. However, our purpose here was to apply principles of mass-balance, critical source area, and targeting to show what could be accomplished by this approach. We believe that our simulations can provide important insights into how to approach P management efforts.

5. Conclusions

DISPLA successfully applies the temporal features of dynamic mass-balance P modeling to the spatial variability across a complex watershed landscape. Long-term simulations using DISPLA can capture the spatial variability of factors influencing P storage and flux and the spatial variability of P storage and flux across a watershed, while accounting for the driving force of P mass-balance as it evolves over time. Our simulations – even in a model watershed where the full extent of natural variability was not captured – demonstrate clearly that areas of P accumulation and therefore of high risk of P export are not uniformly distributed across a watershed or even within a particular land use. Hotspots exist that reflect critical combinations of geophysical and management characteristics. These hotspots change through time and can change in response to management. Finally, DISPLA suggests that some management measures applied in a targeted manner based on certain attributes can significantly reduce the accumulation of P in watershed soils and significantly reduce P export. Results of DISPLA simulations raise important questions about targeting of management measures for watershed P management, and application of DISPLA can help answer those questions.

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